Parton Distribution Functions of the Nucleon: Isolated and Within a Nucleus

and the

Benefits of ν / $\bar{\nu}$-H_2/D_2 Scattering at FNAL

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The Effects of the Nuclear Environment on Nucleon Structure

- As emphasized by Ron, the Nuclear Physics community is devoting considerable time and funds to studying the structure of the nucleon and modifications of that structure for nucleons within a nucleus.

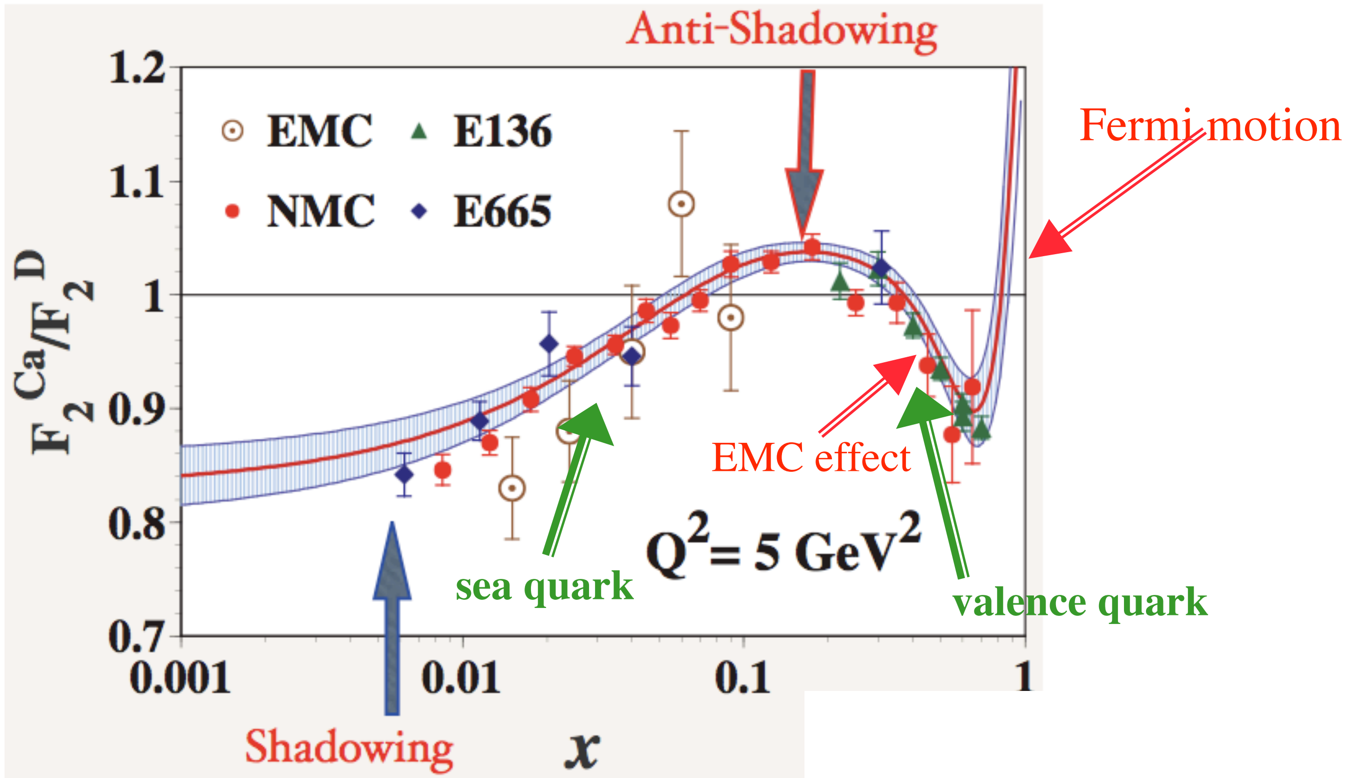
- One of the more fundamental ways of studying the structure of the nucleon is to measure the "structure" functions of the nucleon and use these to determine the nucleon parton distribution functions (PDF). **ν and $\overline{\nu}$ can be particularly powerful here since they choose the flavor of quarks with which they interact!** Nuclear physics community wants to take advantage of this.

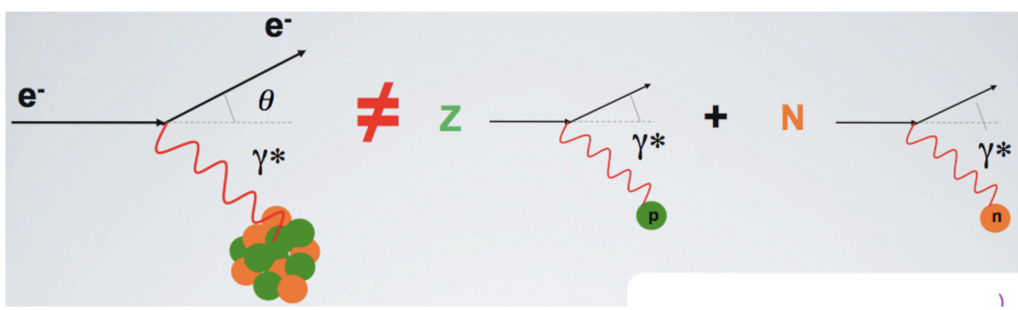
- By measuring the structure functions, and extracting the PDFs, on both hydrogen and deuterium and then comparing these results to the structure functions and PDFs measured on nucleons within a larger A nucleus, we get a direct view of the modifications of the nucleon within a nucleus.

- **Using electro-production, it has been found that, within a nucleus, both DIS and resonance structure functions are modified and parton distribution functions of a nucleon are different than in an isolated nucleon!**

Structure Function Modifications Measured in e/μ – A Scattering: x_{BJ}- Dependent Nuclear Effects

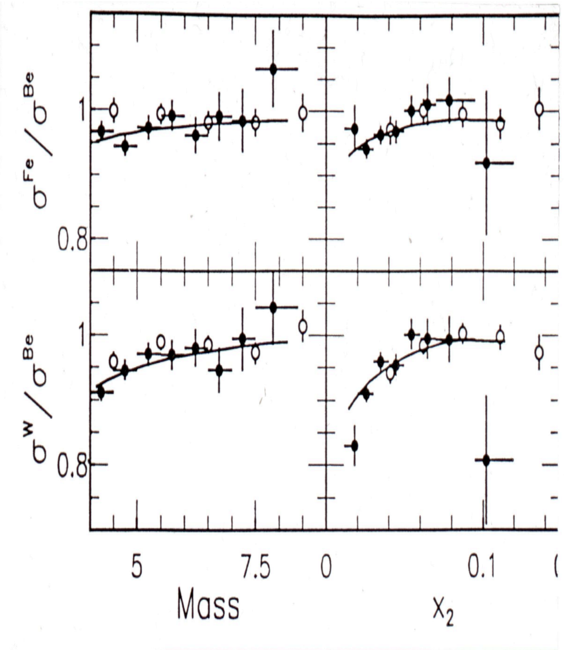
$R_2^{Ca} =$

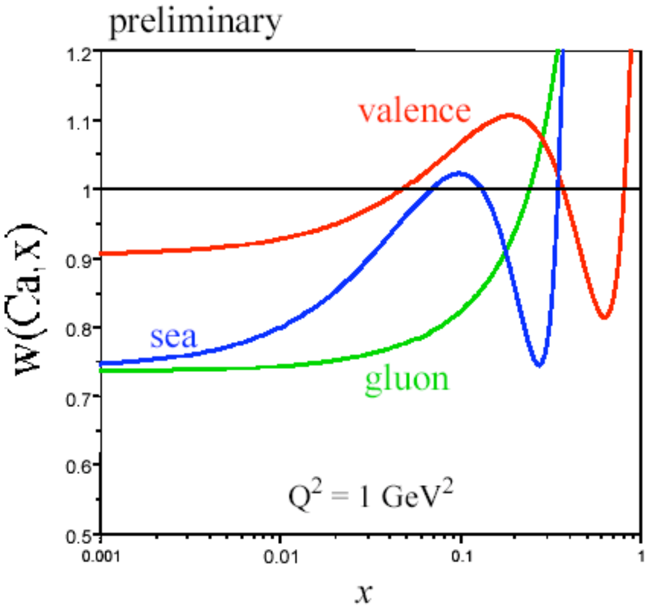




Why the Nuclear Physics Community Wants to Now Study these Nuclear Effects with ν - A

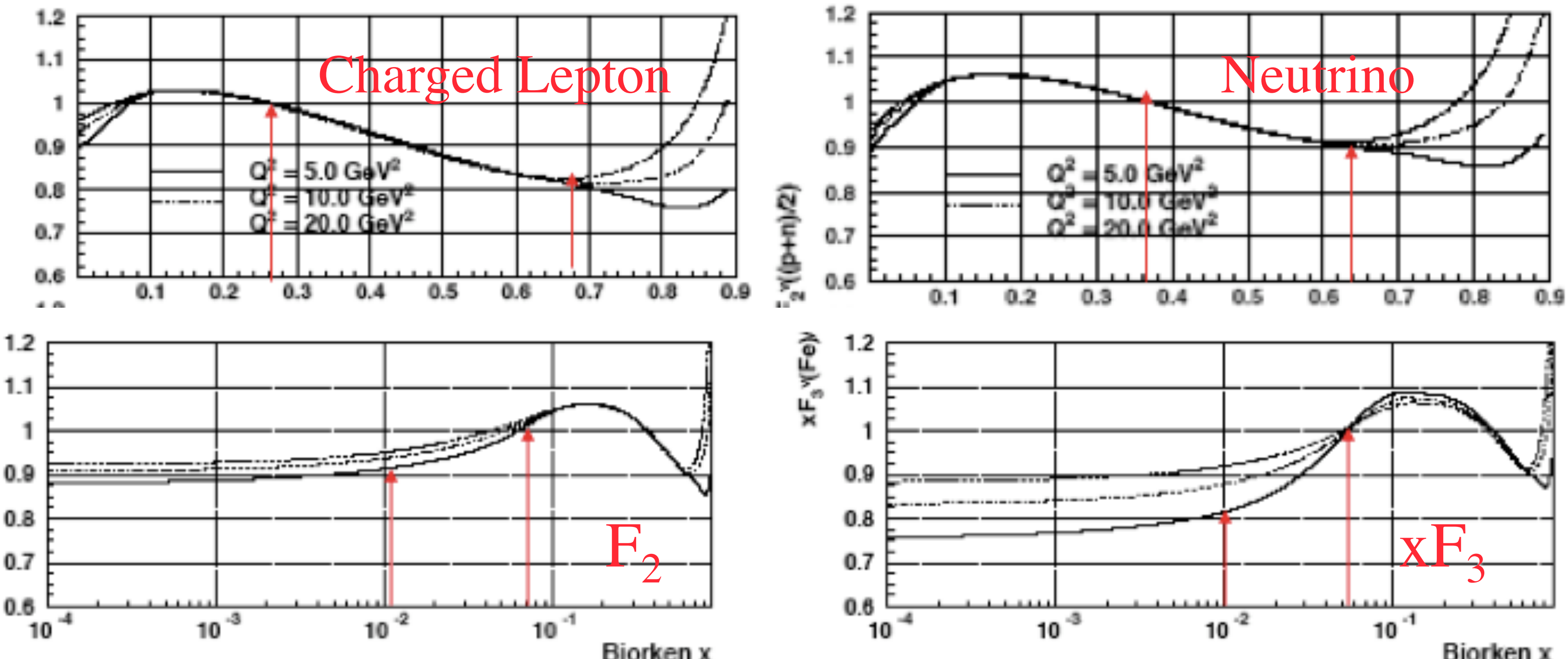
Example: A difference in nuclear effects for valence and sea quarks?





- Nuclear effects similar in Drell-Yan and DIS for $x < 0.1$, the shadowing region. Then no "anti-shadowing" in D-Y while "anti-shadowing" seen in DIS.
- This quantified via **Nuclear Parton Distribution Functions (nPDF).**
- An early attempt to extract nPDFs from electro-production attempted only to look at "valence", "sea" and gluon effects, **not individual quark flavors.**
- If the nuclear effects for valance and sea are different, we expect different nuclear effects for xF_3 compared to F_2 in neutrino scattering. **ν scattering crucial here.**

One Phenomenological Model Available for Neutrinos: It predicts R_2 (μ+Fe) compared to R_2 (ν+Fe) and R_2 (ν+Fe) compared to R_3 (ν+Fe)

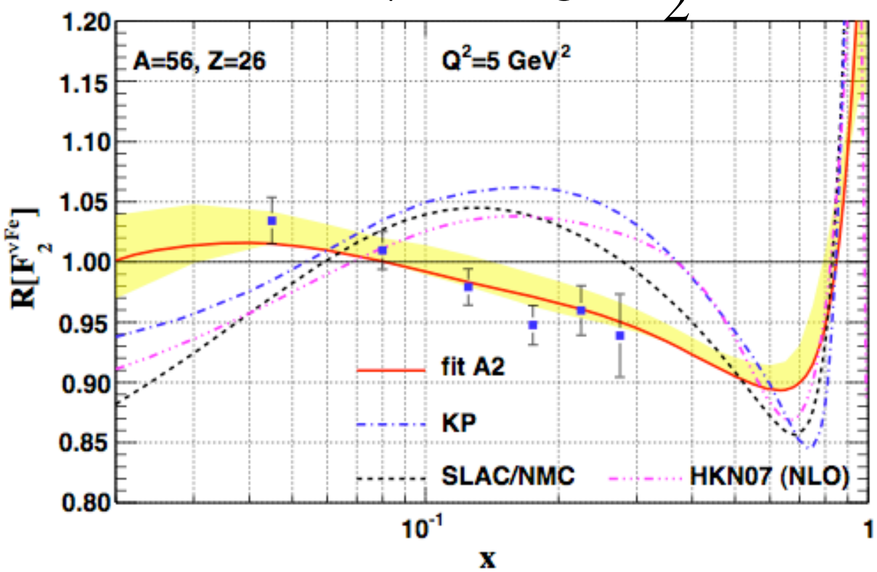


Kulagin-Petti Model of Nuclear Effects
hep-ph/0412425

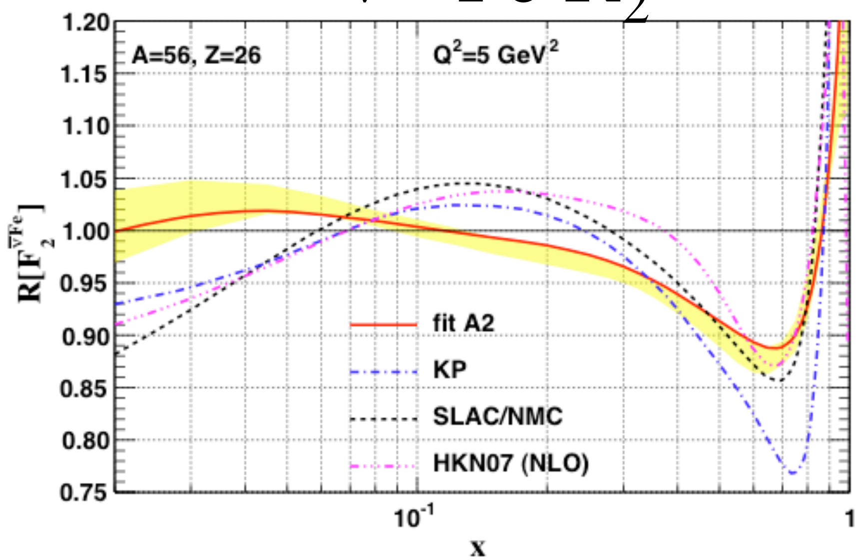
- Now have a CTEQ-MINERνA-Grenoble Project, involving the nuclear physics community, performing a global fit that includes NuTeV ν–Fe data
- We can compute these ratios and compare to this model and charged lepton nucleus scattering.

ν – Fe nuclear corrections different than both e/μ-Fe and model predictions

ν – Fe R_2



$\overline{\nu}$ - Fe $\overline{R_2}$

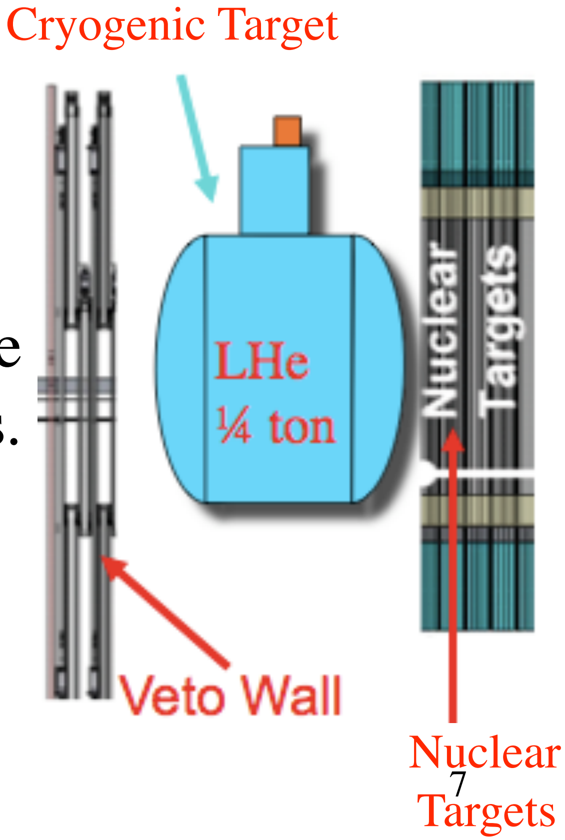


- Need more than one experiment and one nucleus for this study!
- Note: We had to "construct" a ν + D_2 structure function for the denominator from PDFs since there are NO statistically significant data sets of ν + H_2 and ν + D_2 scattering. **We can remedy this situation at Fermilab!**

Studying the Structure of the Isolated Nucleon with ν - H_2/D_2 at Fermilab

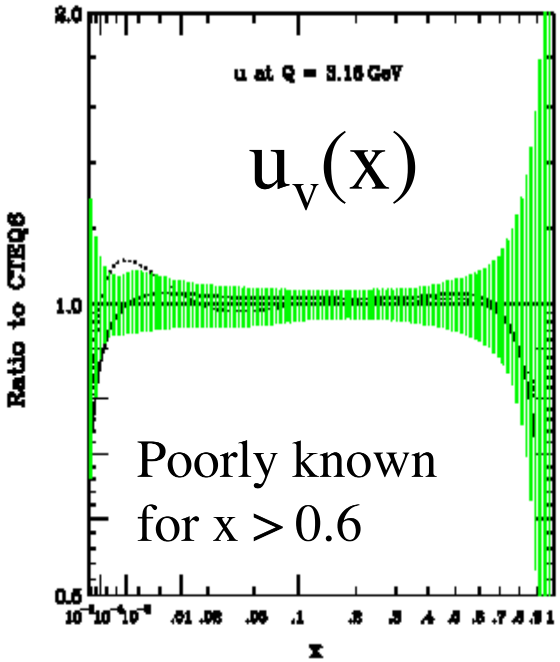
- The nuclear physics community (as well as the HEP community) is very interested in using the high-intensity NuMI ME neutrino beam to extract the isolated nucleon structure functions and resultant PDFs at Fermilab.
- The MINERνA cryogenic target, to be filled with helium, was designed to be capable of a hydrogen or deuterium filling as well.
- Note: different combinations of F_2 and xF_3 give direct access to PDFs including valence quarks.

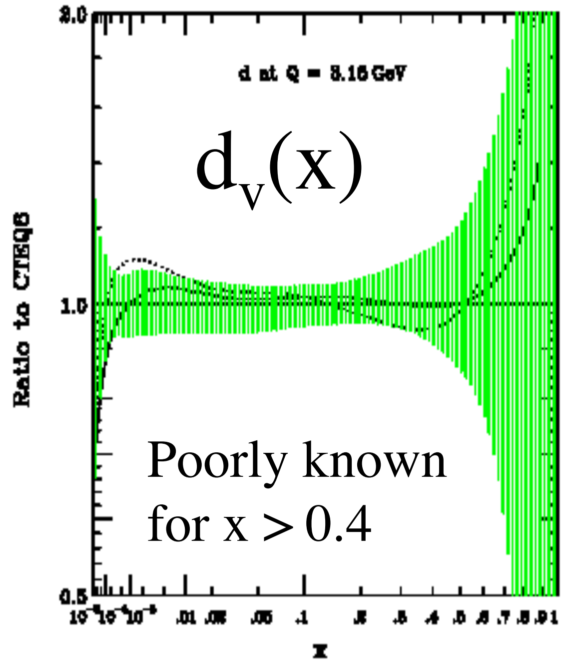
$$F_2^{\nu p}(x) = 2x\left[d(x) + \bar{u}(x) + s(x) + \bar{c}(x)\right]$$
$$xF_3^{\nu p}(x) = 2x\left[d(x) - \bar{u}(x) + s(x) - \bar{c}(x)\right]$$
$$F_2^{\bar{\nu} p}(x) = 2x\left[u(x) + c(x) + \bar{d}(x) + \bar{s}(x)\right]$$
$$xF_3^{\bar{\nu} p}(x) = 2x\left[u(x) + c(x) - \bar{d}(x) - \bar{s}(x)\right]$$

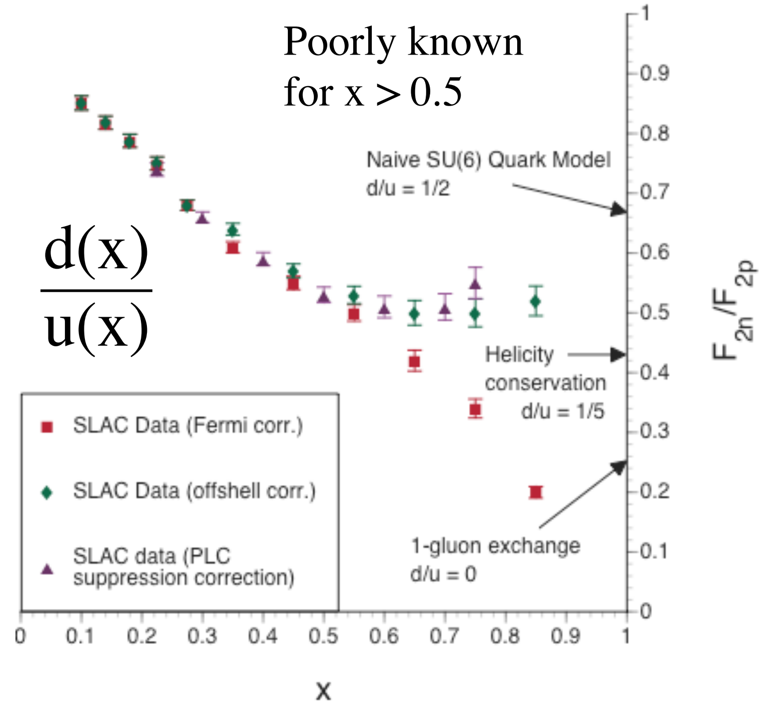


How well do we know nucleon quarks?

Example: Even the <u>**valence quarks at high x poorly known**</u>?



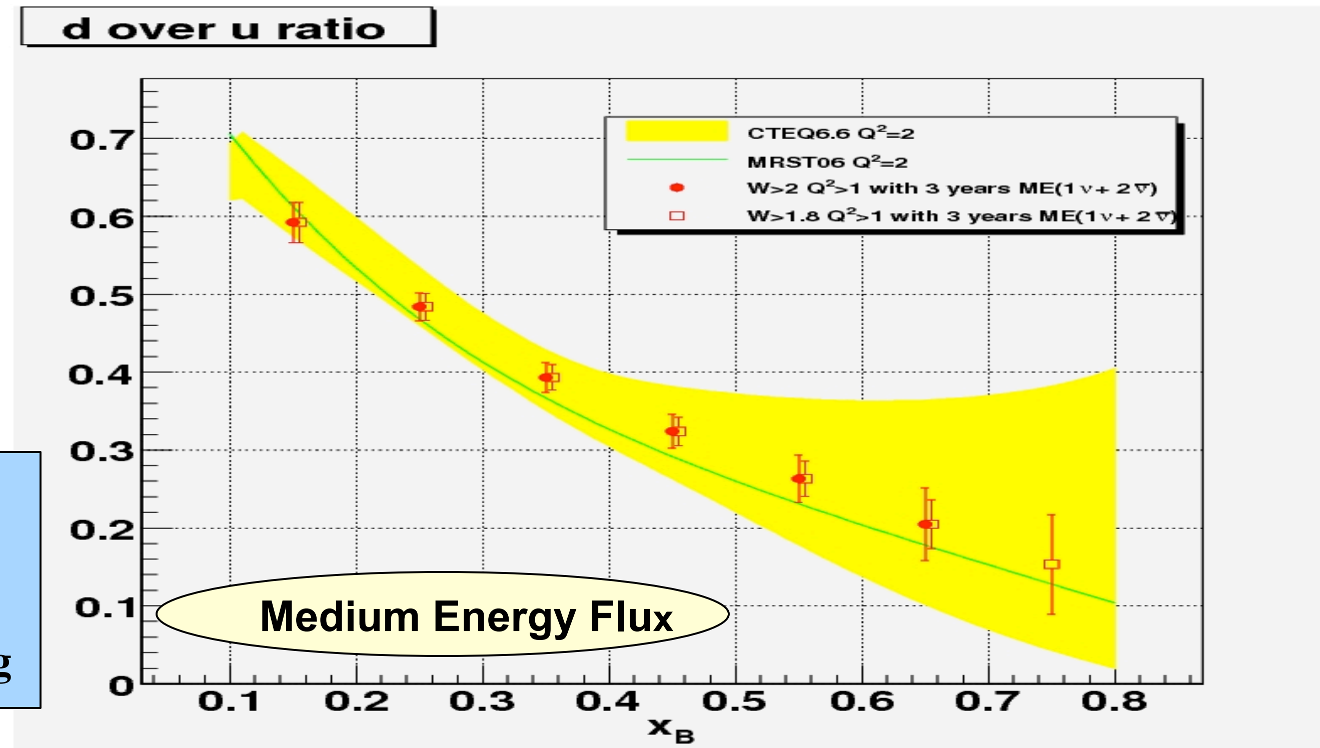




- The shaded green envelopes demonstrate the range of possible distributions from the CTEQ6 error analysis.
- On right is our knowledge of the d/u ratio from e or μ on D_2 and H_2 targets.

A MINERνA H_2 Target with ME beam:
4×10^{20} POT ν, 8×10^{20} POT $\bar{\nu}$

$$\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} \stackrel{*}{\approx} \frac{d}{u}$$



Statistics only, but including:
1) MINERνA acceptance
2) Background subtraction from empty target running

- This takes advantage of both the planned ν the $\bar{\nu}$ runs of NOνA.
- Also sensitive to charge symmetry violations ($d_n \neq u_p$), which gives another look at the structure of the nucleon.

Summary

- The Nuclear Physics Community is anxious to use **neutrinos** to explore the structure of the isolated nucleon and then see how this structure is modified within a nucleus.

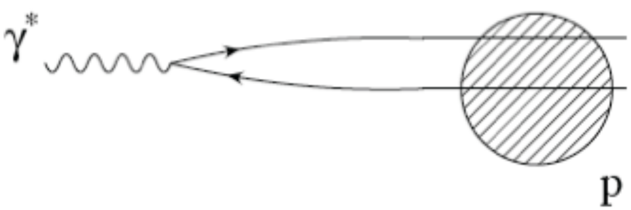
- The consequent isolated nucleon PDFs and the nuclear PDFs from neutrino scattering can then be compared to those extracted from charged lepton scattering and differences understood in terms of nucleon structure.

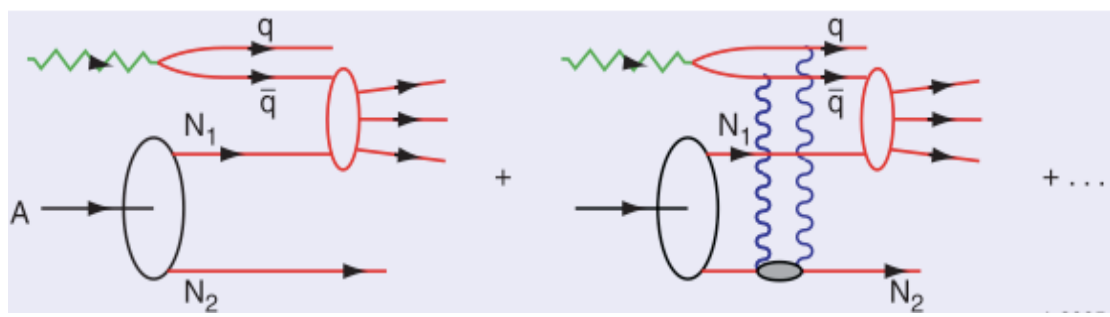
- To measure the isolated nucleon structure functions with neutrinos, we need to fill the (available) MINERνA cryo target with hydrogen and then deuterium.

- The nuclear physics community strongly supports this use of the MINERνA cryo target.

Nuclear Shadowing and Anti-Shadowing: Models say **Should be DIFFERENT for neutrinos**

- Shadowing/Anti-shadowing: Destructive/Constructive interference of multiple coherent scattering off nucleons in nucleus – NO FLUX reaches the downstream nucleons in shadowing.
- Think of Vector Meson Dominance and propagator interacts with the nucleus as a q-$\bar{q}$ pair (a pion) interacting with upstream nucleons. At small x_{Bj} the q-$\bar{q}$ pair fluctuation is long-lived → long coherence length.
- Occurs in both resonance production and DIS scattering.
- Shadowing and Anti-shadowing expected to be different in neutrino scattering compared to electro production. Axial-vector current has longer coherence length?





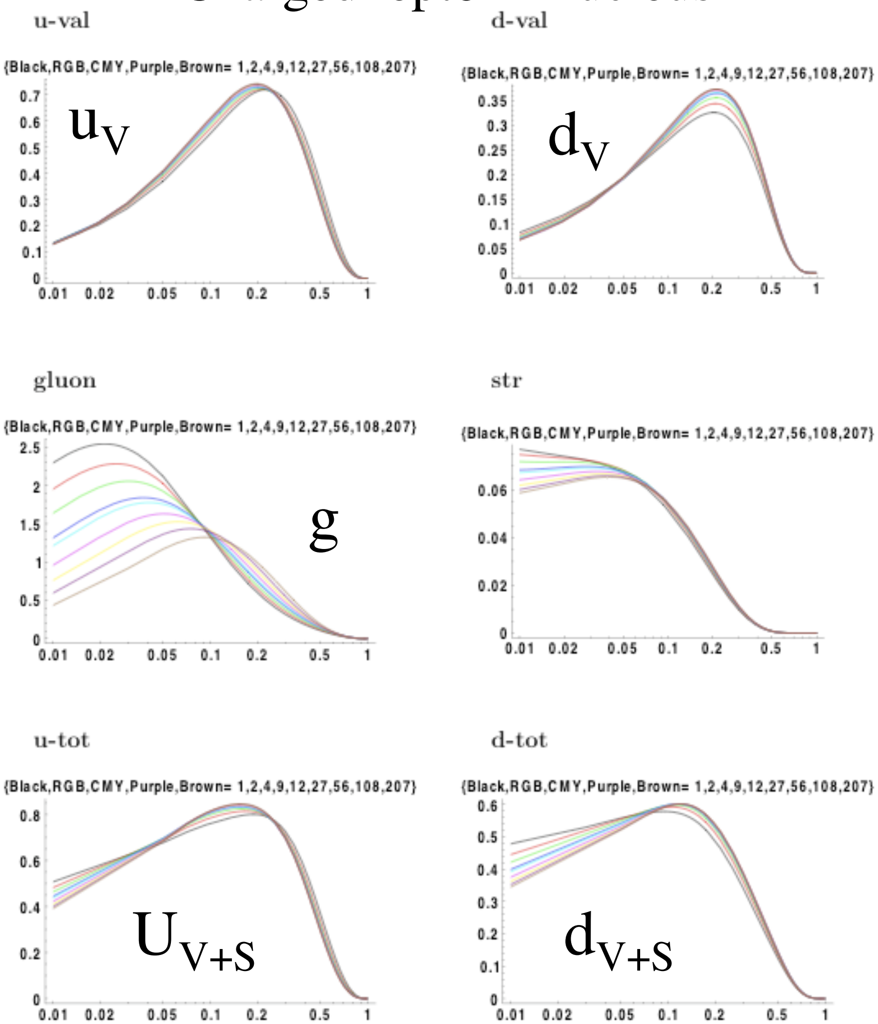
The "EMC" Effect: Models say **Should be THE SAME for neutrinos**

- Conventional nuclear physics based explanations
  - Fermi motion alone and Fermi motion plus binding unable to explain the effect
  - Even more sophisticated approaches (spectral function) fail unless one includes "nuclear pions"
  - Size of contributions from nuclear pions typically used in DIS calculations inconsistent with nuclear dependence of Drell-Yan
- "Exotic" effects such as medium effects on quark distributions themselves: dynamical rescaling, multi-quark clusters, etc.
- Still discussing what is the "correct" explanation, however no explanation expects any difference between ν – A and e/μ – A scattering.

Nuclear Parton Distribution Functions

{Black,RGB,CMY,Purple,Brown= 1,2,4,9,12,27,56,108,207}

Charged lepton - nucleus



(Neutrino – nucleus)